

# **Modeling and Simulation of MEMS Microthrusters**

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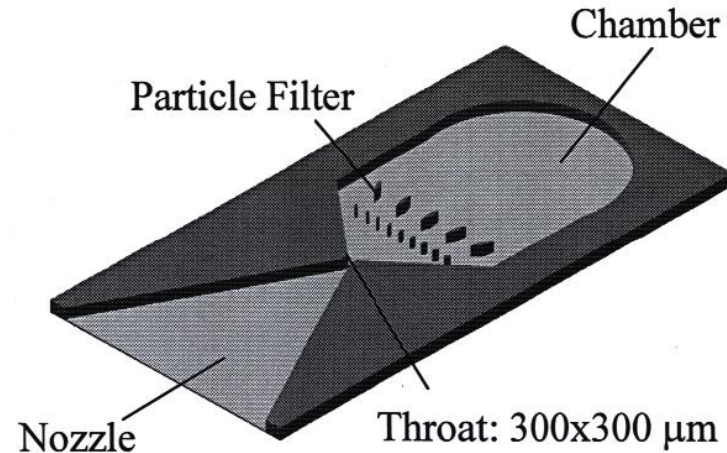
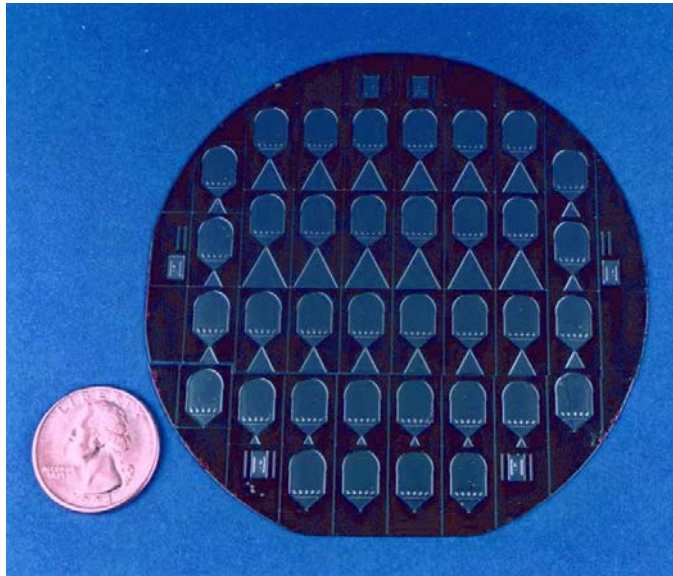
**June 21-25, 2004**

**Istanbul, Turkey**

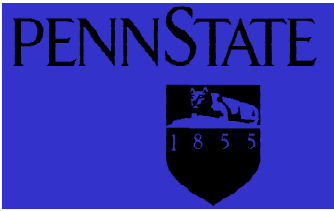
**AFOSR/EOARD Symposium on Energy  
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# MEMS-Based Propulsion



- To enable formation flying concept new propulsion systems are needed that can deliver precise impulse bits under strict mass, size and power limitations.
- Various MEM-based propulsion systems are considered for such missions: cold and heated gas, bipropellant, catalytic and solid decomposition thrusters.

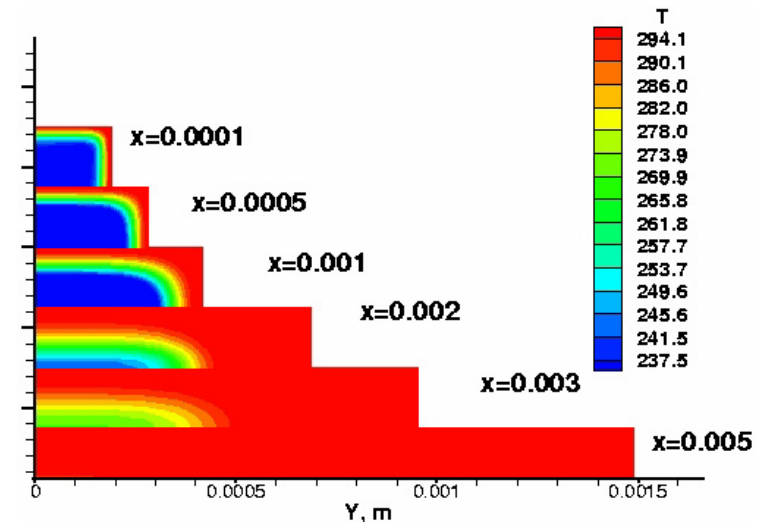


# Physics of Micro-nozzle Flows

- Due to the reduced physical size, frictional surface effects can dominate the gas flow in microthrusters.

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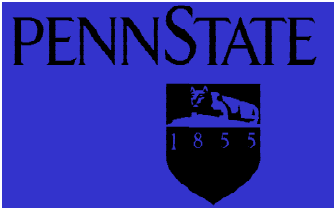
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.



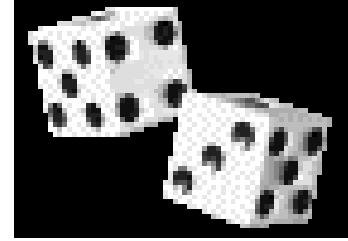
Comparison of boundary layers for traditional axisymmetric vs MEMS flows.

Development of 3D boundary layer in a cold gas flow.

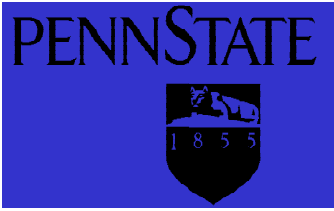
- In addition, wall temperature, heat transfer, and heat fluxes are major controlling factors for microthruster performance, yet it is often an unknown in the system design.



# The DSMC Method



- 
- A simulation tool for modeling chemically reacting flows in *rarefied/transitional* environments.
  - $Kn = \mathcal{M}_{ref}$ ,  $\lambda$  = mean free path,  $l_{ref}$  = reference length
    - Continuum: Navier-Stokes,  $Kn \leq \sim 0.001$
    - Transitional: DSMC,  $Kn \geq \sim 0.01$
  - Developed by G. Bird to obtain a solution of the Boltzmann equation,
    - follow the motion of many virtual molecules on a grid, for a series of time steps,
    - calculate particle collisions using Monte Carlo techniques.
    - model gas-surface interactions,
    - using conservation relationships, obtain changes in internal energies and velocities of the components.
  - Flows around spacecraft and micro-propulsion devices can be modeled by DSMC because they have similar  $Kn$ .

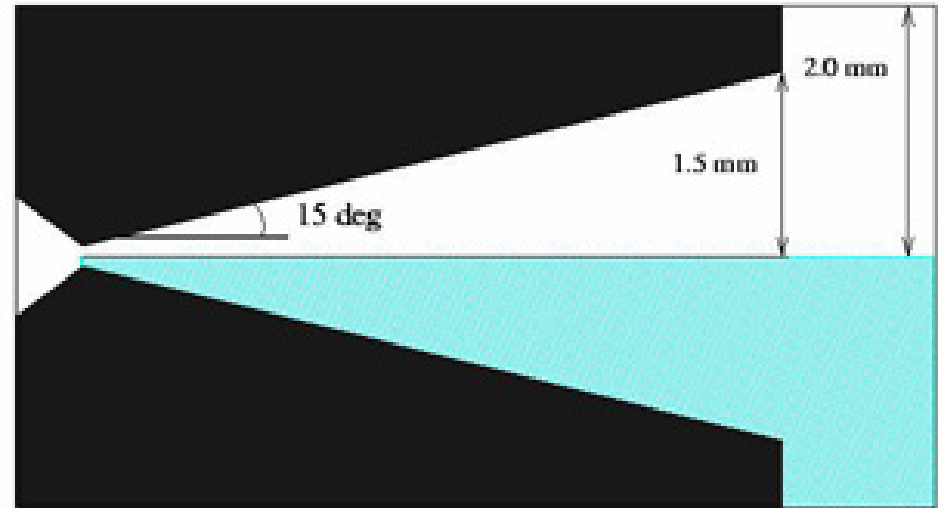
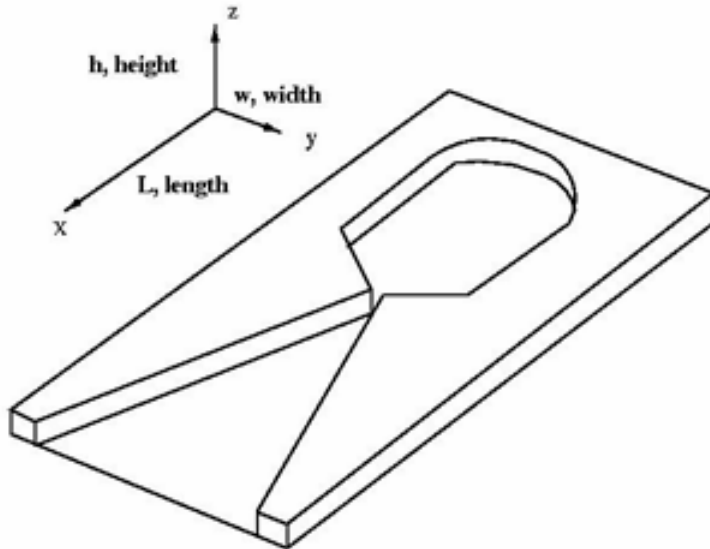


# Outline of Talk

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- **Cold gas thrusters - effects of**
  - geometry: 3-D , 2-D, axisymmetric,
  - gas surface model,
  - performance.
- **Higher temperature gas thrusters - effects of,**
  - flowfield dependence on  $T_o, p_o$
  - gas- surface interaction,
  - stagnation conditions and internal energy on performance.
- **High-temperature gas thrusters with variable  $T_{wall}$ ,**
  - coupled DSMC/FEM method,
  - variable material cooling conditions,
  - time-dependent calculations of thrust and material characteristics.

# Cold Gas Thrusters - Geometry



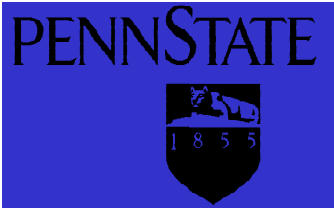
## •3D flat nozzle

- XY plane expansion angle  $\alpha = 15^\circ$
- throat width  $w = 300 \mu\text{m}$
- throat height  $h = 300 \mu\text{m}$
- Area ratio  $A_e/A^* = 10$

## •2D nozzle, neglect surfaces in x-y plane, for $z=0, h$

## •Axisymmetric

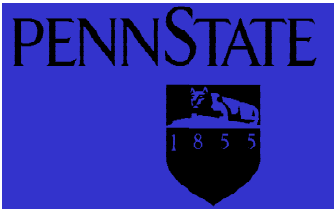
- expansion angle  $\alpha = 15^\circ$
- throat radius  $R_t = 150 \mu\text{m}$
- Area ratio  $A_e/A^* = 100$



# Cold Gas Thruster - Conditions

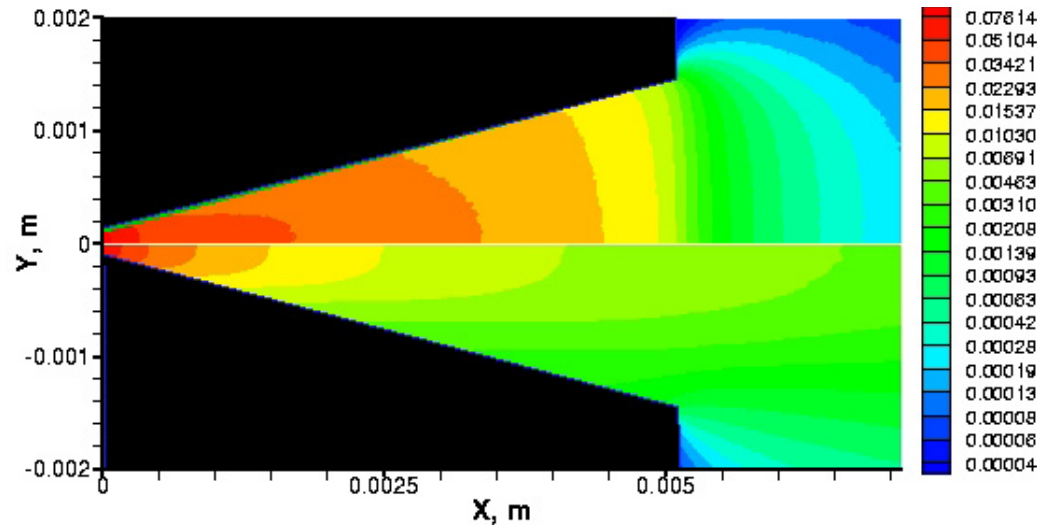
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- Test gas  $N_2$
- Stagnation temperature and pressure  $T_c = 300 \text{ K}, P_c = 10 \text{ kPa}$
- Critical temperature and pressure  $T_t = 250 \text{ K}, P_t = 5.2 \text{ kPa}$
- Wall temperature  $T_w = 300 \text{ K}$
- Knudsen number (mean free path/char length)  $Kn = 5 \times 10^{-3}$
- Reynolds number (mom/viscous ratio)  $Re = 200$

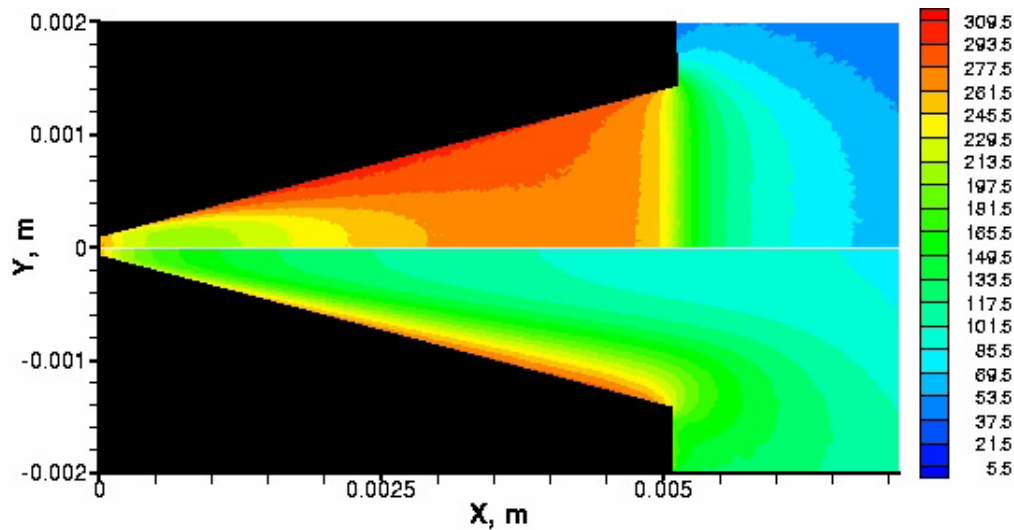


# Cold Gas - Effect of Geometry

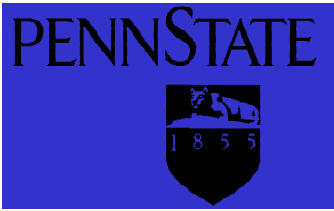
Top - 3-D, Bottom -2-D



- Density,  $\text{kg/m}^3$
- Greater flow expansion in 2-D case.

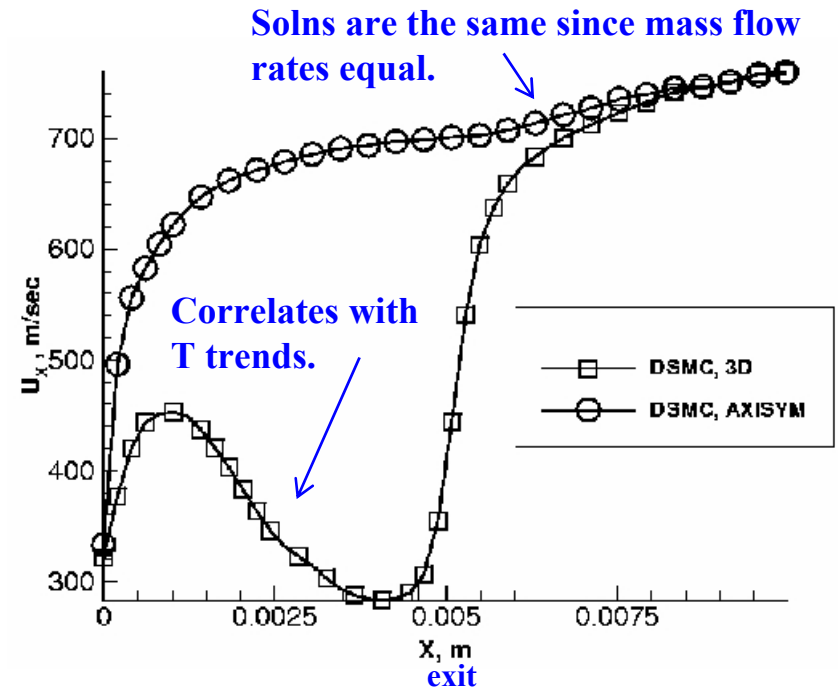
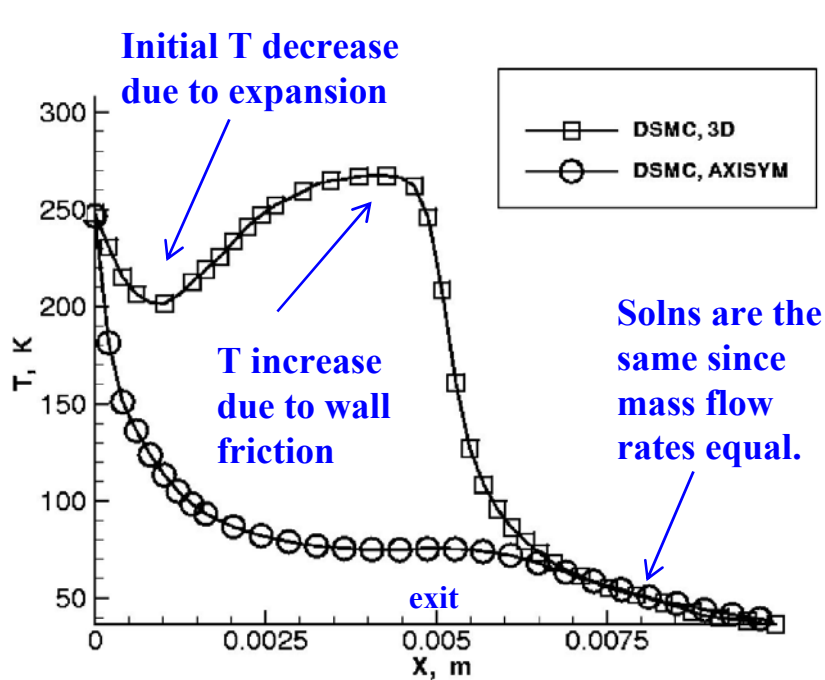


- T, K
- More heat transfer to the wall in the 3-D case.

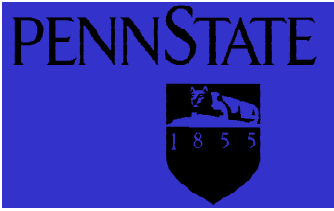


# Cold Gas - Effect of Geometry

## 3-D vs. Axisymmetric

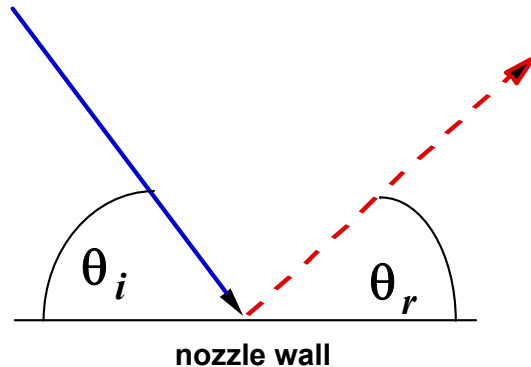


- 3-D vs axisymmetric shows that the degree of wall surface area is important.
- For supersonic nozzle flow into a vacuum,  $U_x$  should be a maximum at the exit.
- Instead, extremum  $U_x$  is located upstream due to subsonic region at the walls.

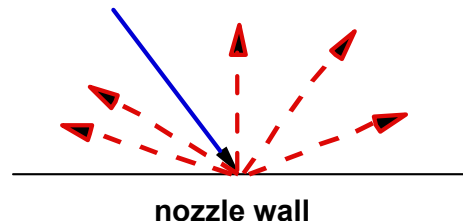


# Kinetic, DSMC Gas-Surface Wall Models in Micro-nozzle Flows

## Specular reflection



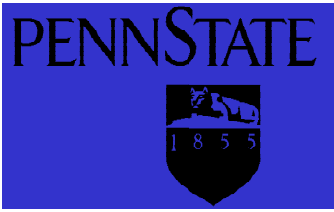
## Diffuse reflection



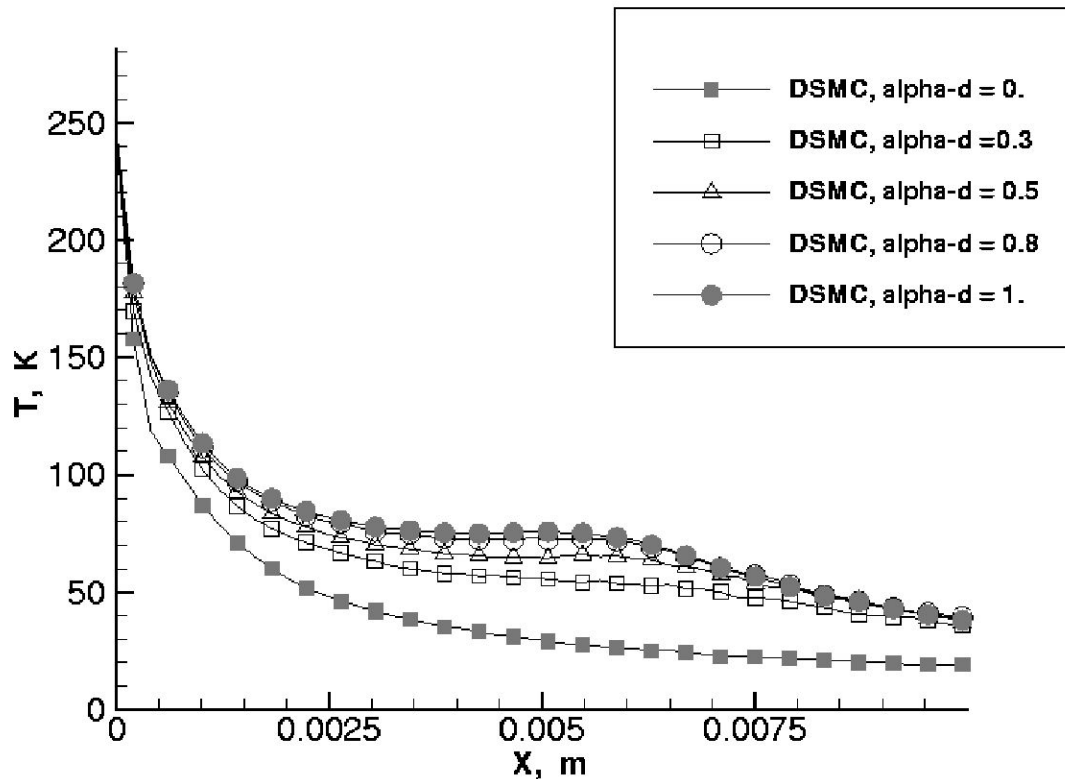
## •Two types of gas-surface interactions

- Specular - incident and reflected tangential momentum are the same,
- Diffuse - all reflected directions are equally probable, wall acts like an emitting source of particles at  $T_{\text{wall}}$ ,

- Interaction is specified by with accommodation coefficients for
  - Normal momentum, tangential momentum, and energy (heat transfer)
  - Values between 0,1 and closer to 1 for spacecraft materials.
- Continuum methods are partially corrected with wall slip-jump boundary conditions.
- Accommodation  $\sim 1$  generates large, viscous boundary layers.



# Cold Gas Thrusters - Effect of Gas-surface model



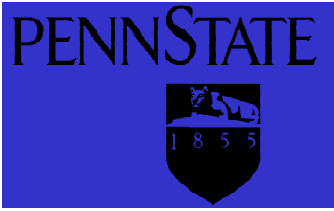
Translational T profiles along the nozzle axis for different  $\alpha_d$  in an axisymmetric micronozzle.

- Definition of tangential momentum accommodation coefficient,

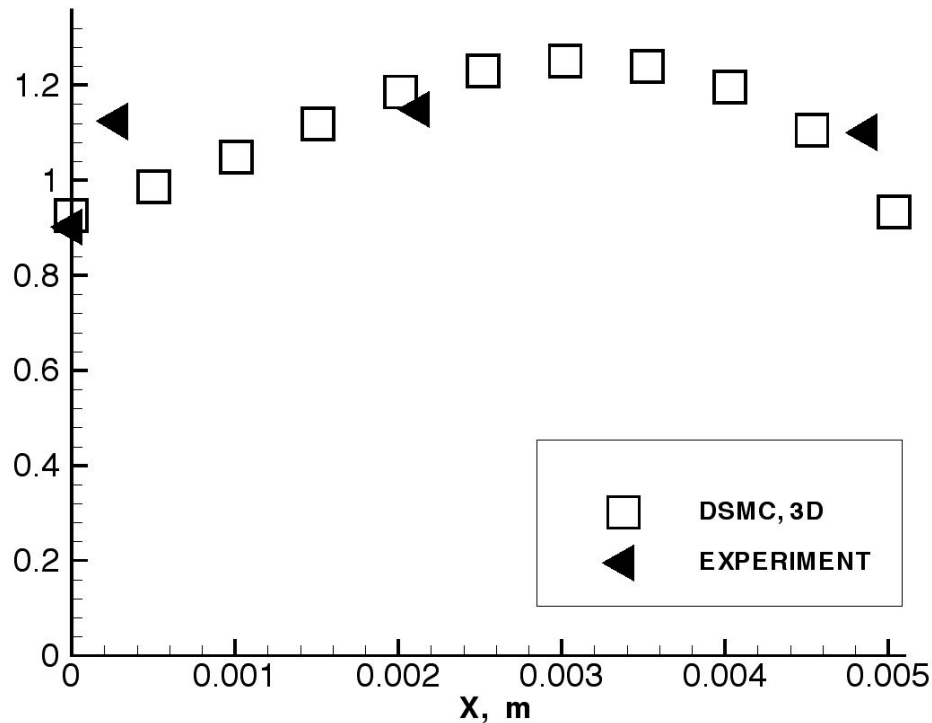
$$\alpha_d = (P_{\tau i} - P_{\tau r}) / P_{\tau i}$$

- Experiments show that  $\alpha_d = 0.8$  for silicon.

- 3-D calculations showed only 1% difference for  $\alpha_d = 0.8$  and 1.

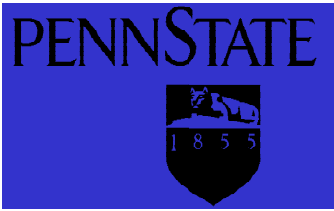


# Cold Gas Thrusters - Performance



| Case    | Thrust (mN) | I <sub>sp</sub> , (sec) |
|---------|-------------|-------------------------|
| AS NS   | 1.07        | 65.62                   |
| AS DSMC | 1.03        | 65.5                    |
| 2D NS   | 1.17        | 69.45                   |
| 2D DSMC | 1.10        | 68.74                   |
| 3D DSMC | 0.93        | 56.61                   |

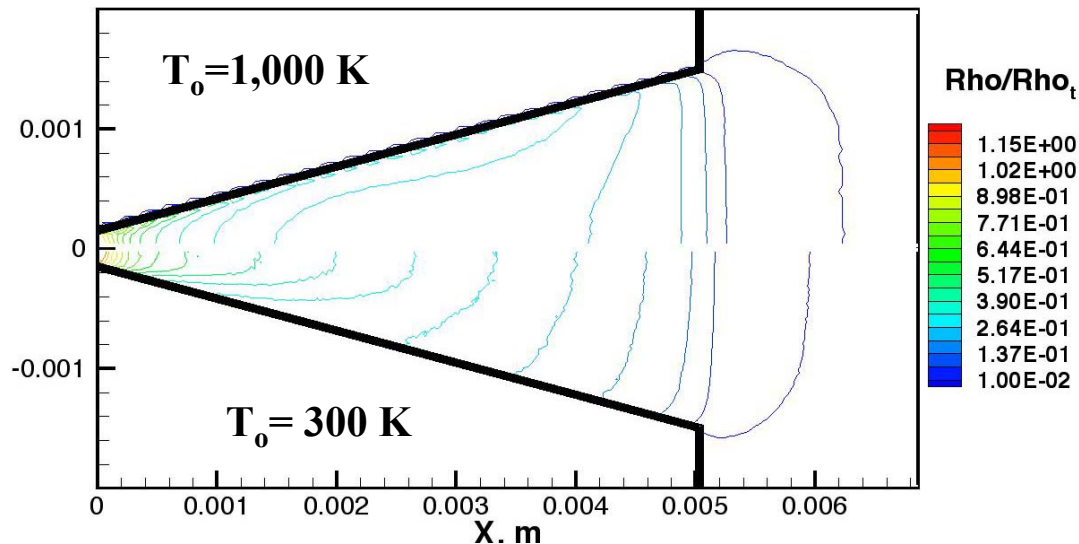
- Comparison of 3-D calculations with data show good agreement.
- 2-D assumption is poor and over predicts thrust levels of geometry.
- Wall effects in 3-D case reduce thrust (20%) and specific impulse cf to 2-D.



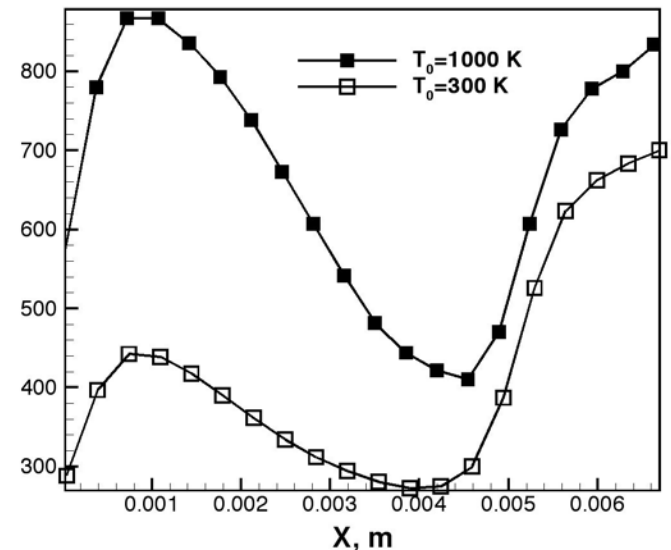
# Higher-Temperature Thruster Flows

Full wall accommodation,  $Re_t \sim 200$ ,  $T_w = 300$  K, 3-D nozzle

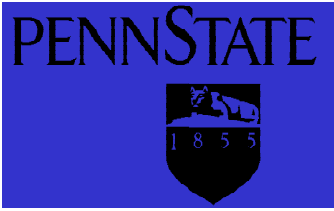
Normalized density



$U_x$  along centerline

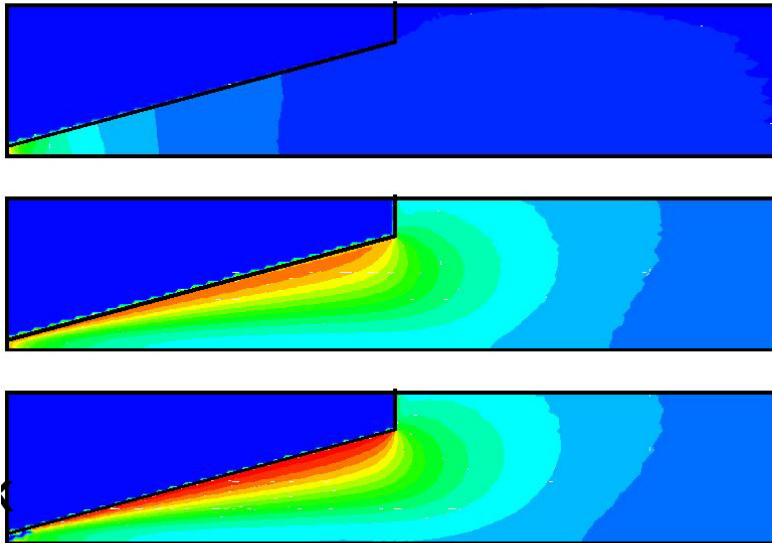


- Flows at both temperatures are dominated by surface interactions, but structure is different.
- $I_{sp} = 56.6$  and  $61.5$  for  $T_0 = 300, 1000$  K, respectively.
- Increase in  $I_{sp} \ll$  than for comparable axisymmetric case due to larger surface-area-volume ratio.



# Comparison of Flows for Different Gas - Surface Models and $T_0$

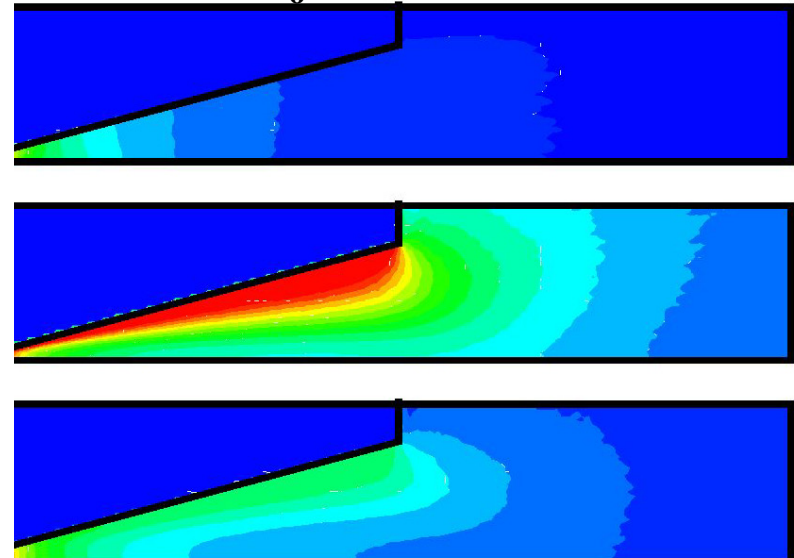
$T_0=300$  K



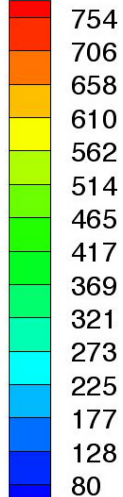
T, K



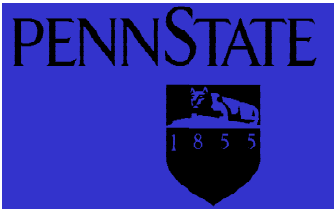
$T_0=1,000$  K



T, K

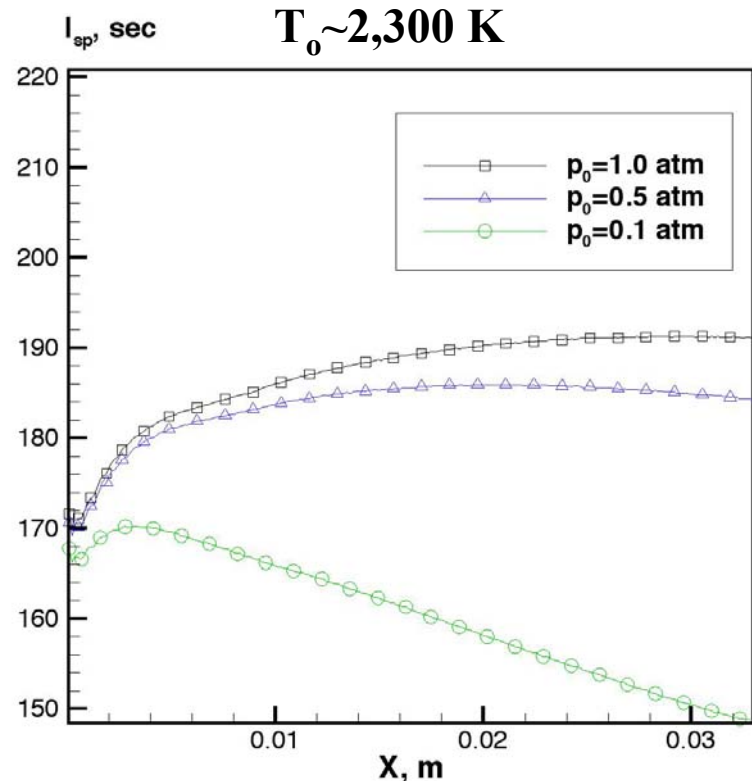
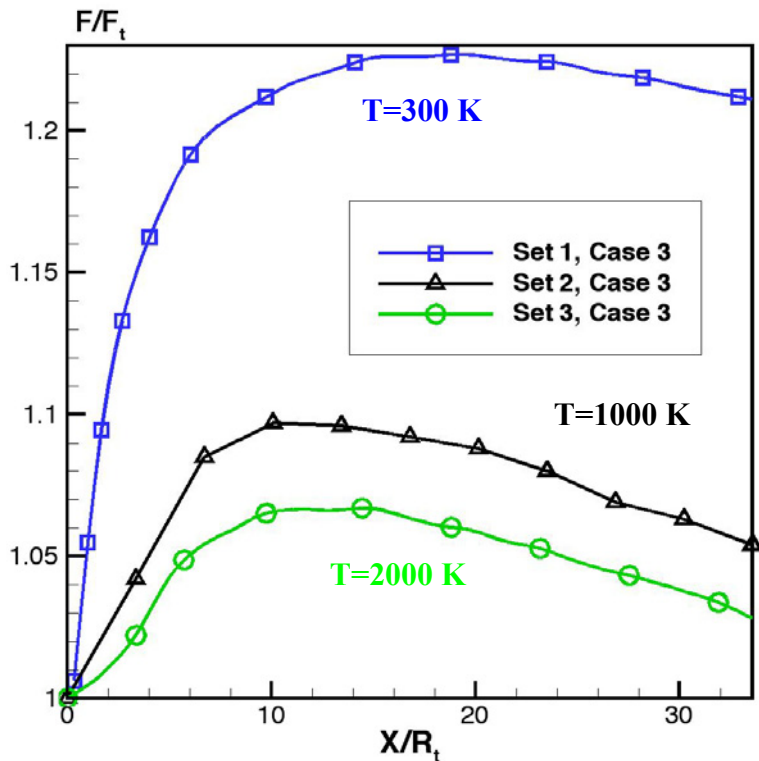


1. “Specular” = ideally smooth, no momentum or energy transfer (TOP),
2. “Diffuse, adiabatic” = av tangential momentum of reflected molecules = 0, no energy transfer with wall (MIDDLE).
3. “Diffuse,  $T_w=300$ ” = both momentum and energy transfer occurs with wall (BOTTOM).

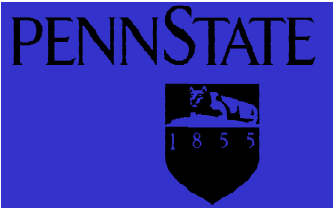


# Effect of $T_0$ and $P_0$ on Performance

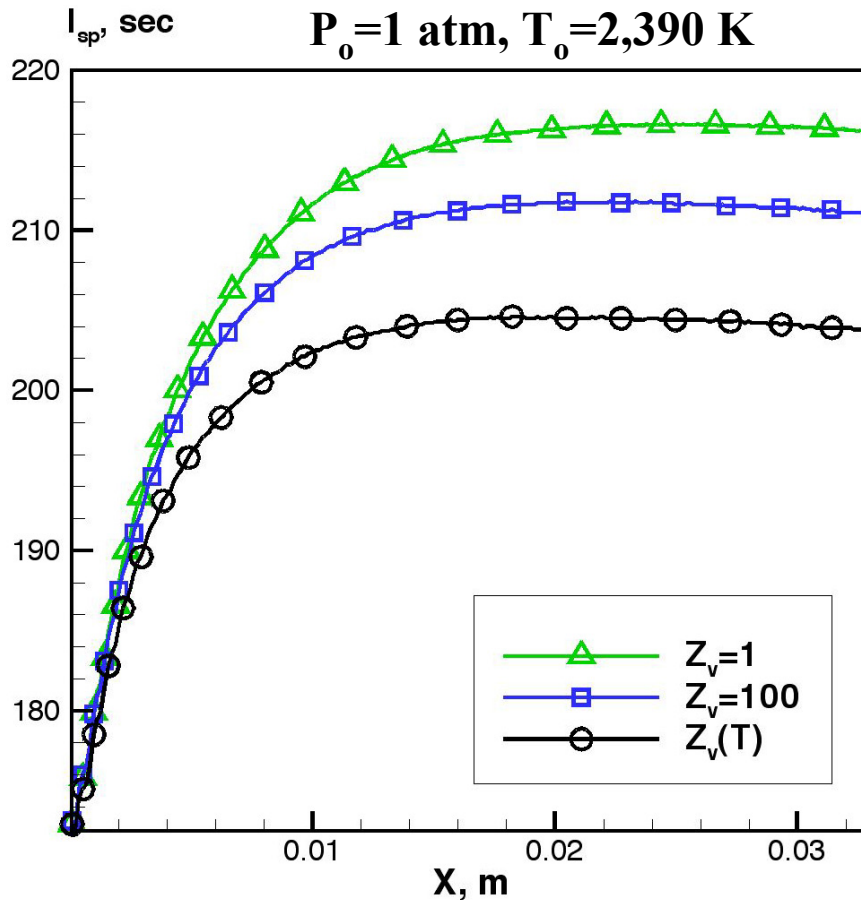
Axisymmetric nozzle, Diffuse wall,  $T_w=300$



- For high  $T_0$ , a shorter nozzle would give better performance at lower Re.
- Need to optimize geometry of high temperature nozzles.
- For lower pressures, the peak value of  $I_{sp}$  is closer to the nozzle throat.

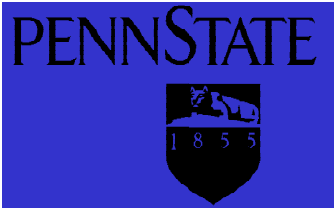


# Effect of Internal Energy\* on Performance

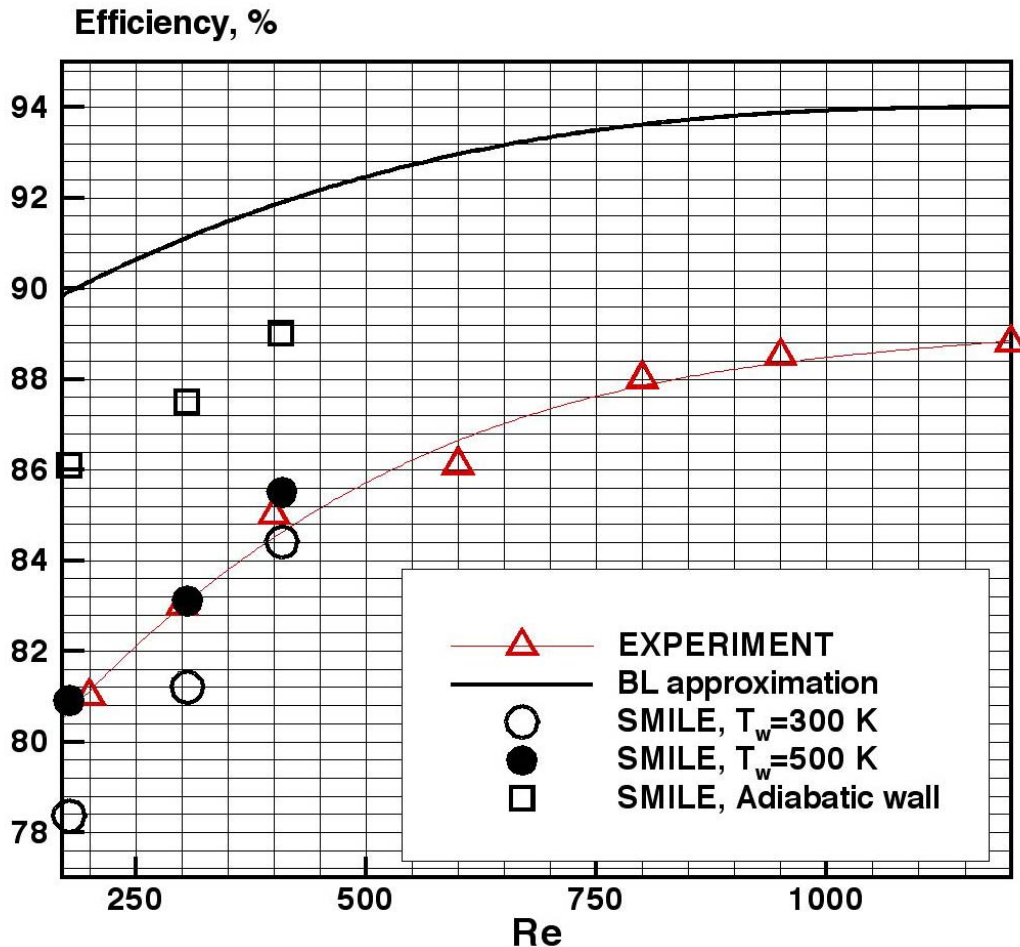


- Axisymmetric nozzle, hydrogen air mixture  $\Rightarrow$  66.1%  $N_2$ , 32.4%  $H_2O$ , and 1.5%  $H_2$
- High T polyatomic gas, VT becomes important.
- Represent VT by  $Z_v$  relaxation numbers in Larsen-Borgnakke model:
  1.  $10^4 < Z_v(T) < 10^6$
  2. Constant  $Z_v = 1$  and 100.
- Faster VT relaxation increases nozzle performance.

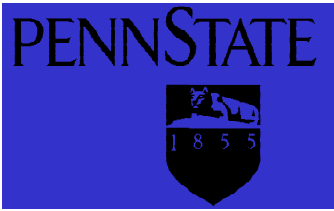
\*For cold gas thrusters, TR relaxation is the dominant internal energy transfer mechanism.



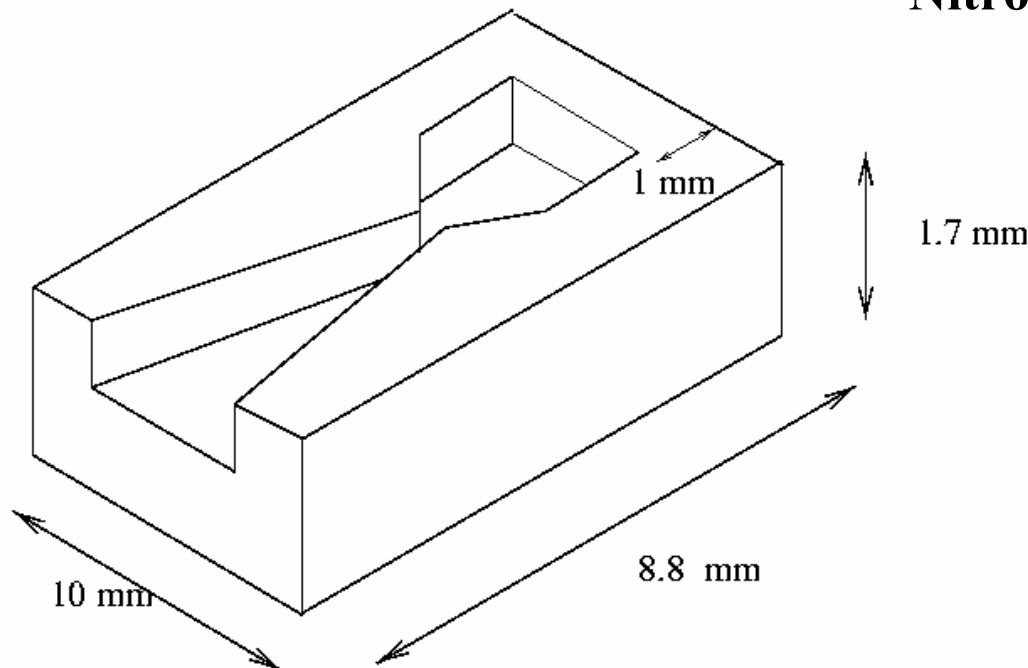
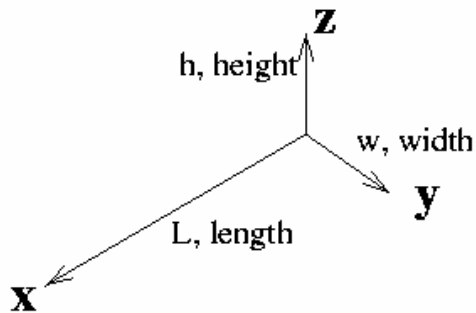
# Comparison of Calculated and Measured Efficiencies for Axisymmetric Nozzles



- Experimental data did not specify  $T_w$ .
- Good agreement between measurements and modeling for  $T_w=500$  K and complete accommodation.
- $I_{sp}$  sensitive to wall conditions.
- *Need a predictive capability to determine both material and gas properties for micropropulsion devices.*

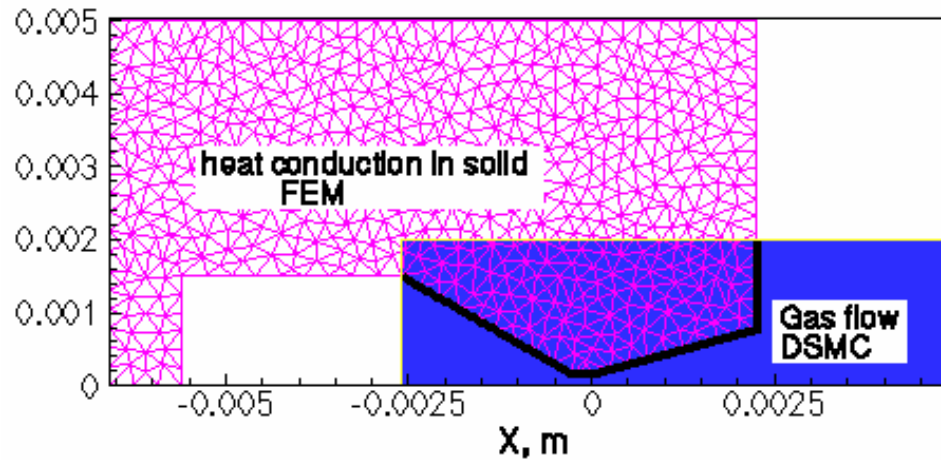


## Geometry and Flow Conditions Schematic of NASA-Glen Microthruster



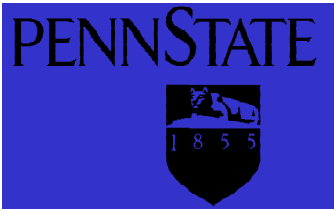
- 30 deg converging part
- 15 deg diverging part
- Exit to throat area ratio of 5
- Throat:  $300\mu\text{m} \times 600\mu\text{m}$
- Nitrogen flow:
  - $P_o = 0.1$  and  $0.5$  atm,
  - $T_o = 2000$  K,
  - $Re = 35$  and  $175$ , respectively.

# Coupled Thermal and Gas Dynamic Computational Approach



**Computational domain for 2D calculations**

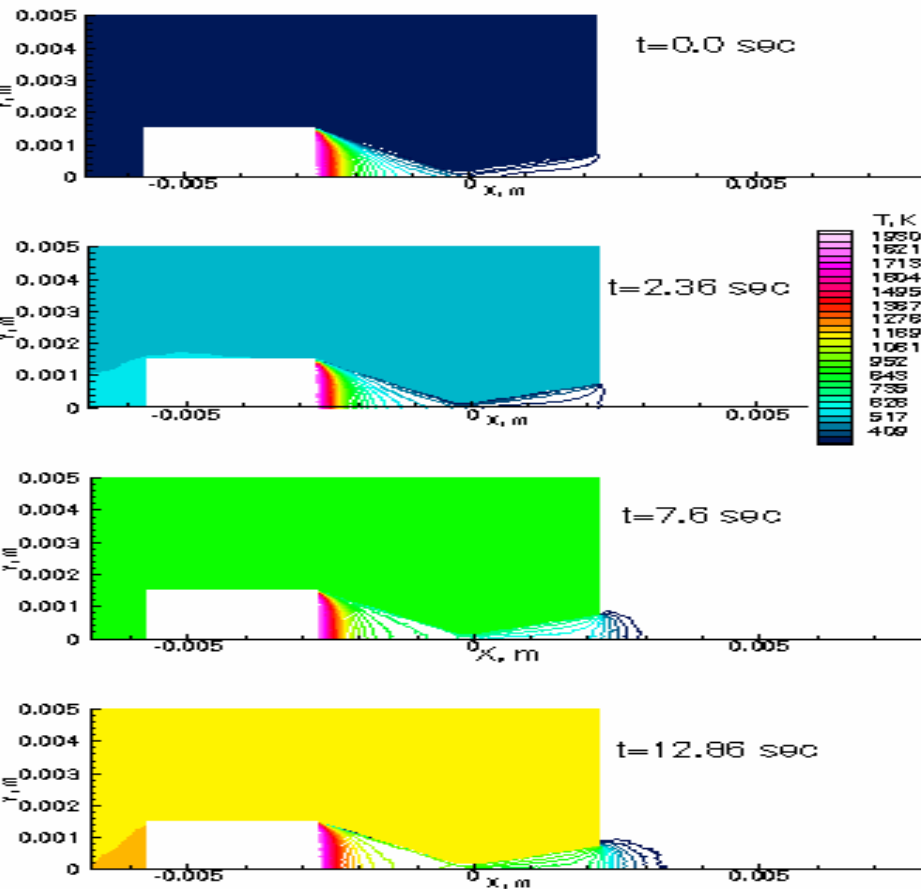
- **Based on the solution of the heat transfer problem using finite element method coupled to the DSMC gas flow solution.**
- **Coupling between material thermal response and flow by using DSMC heat fluxes as the boundary conditions for the heat conduction problem.**
- **The wall temperature calculated in the heat transfer simulations is, in turn, applied as a boundary condition for DSMC calculations.**



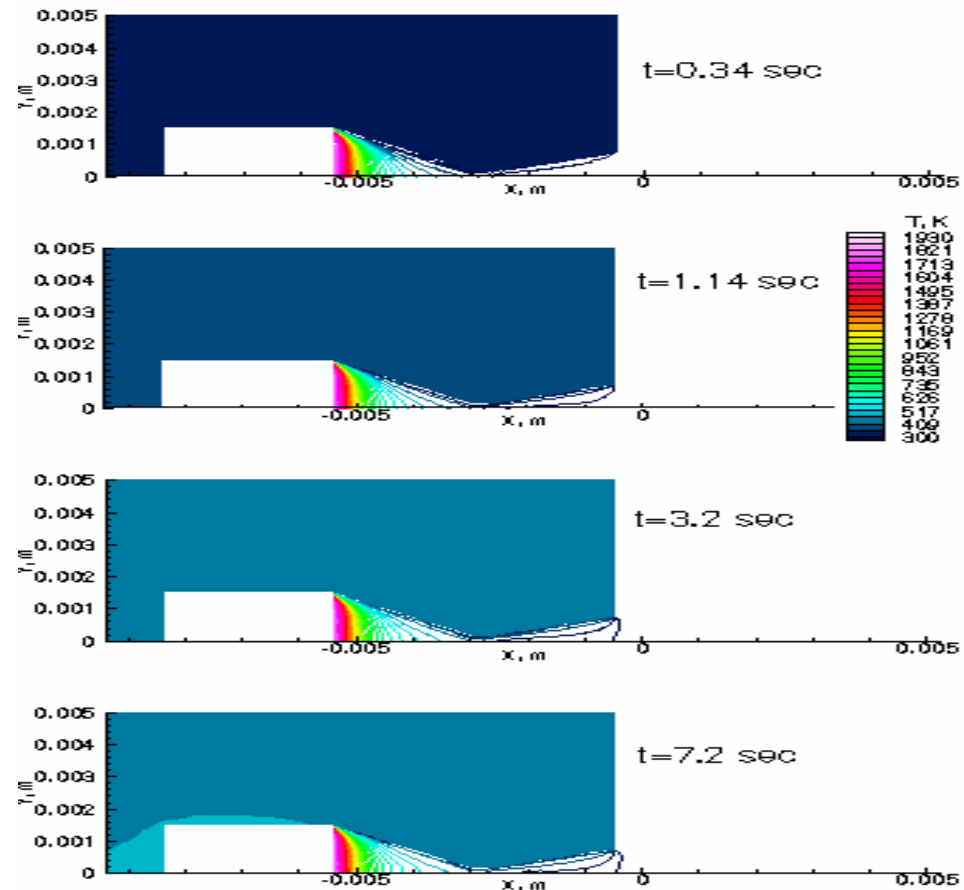
# Material thermal response: 3D

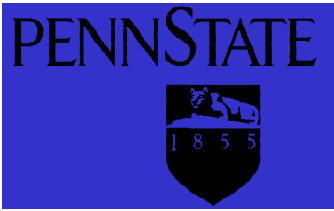
Time variation of the temperature fields for 0.1 atm

## Thermally Insulated



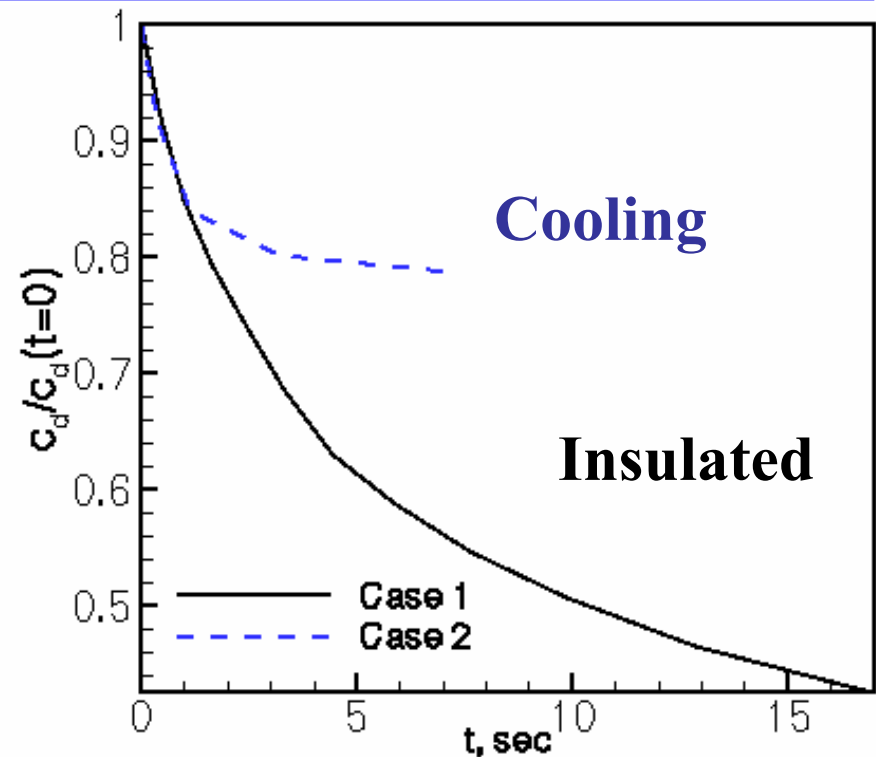
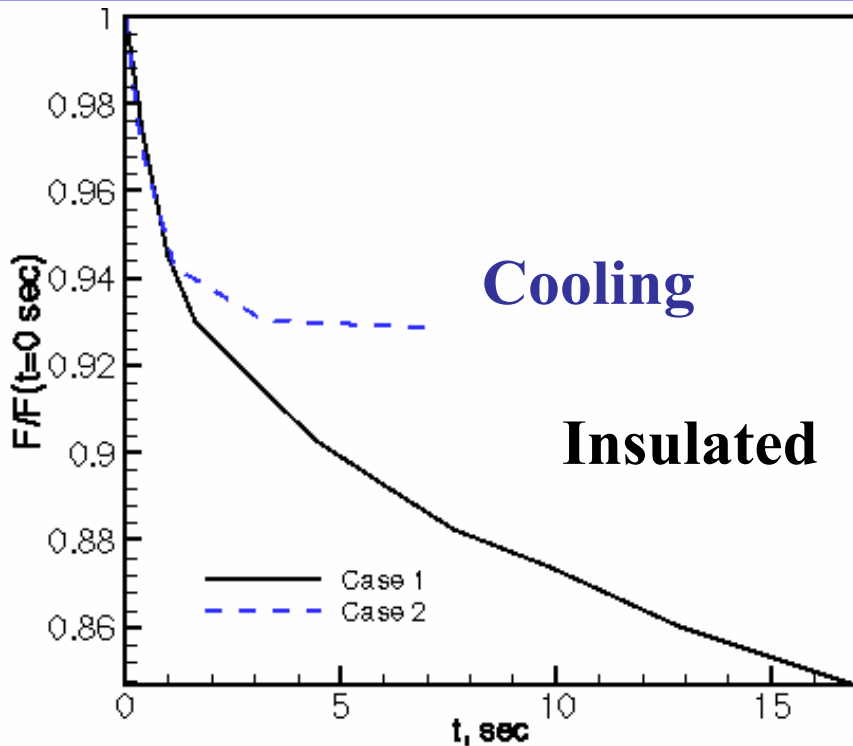
## Active Cooling





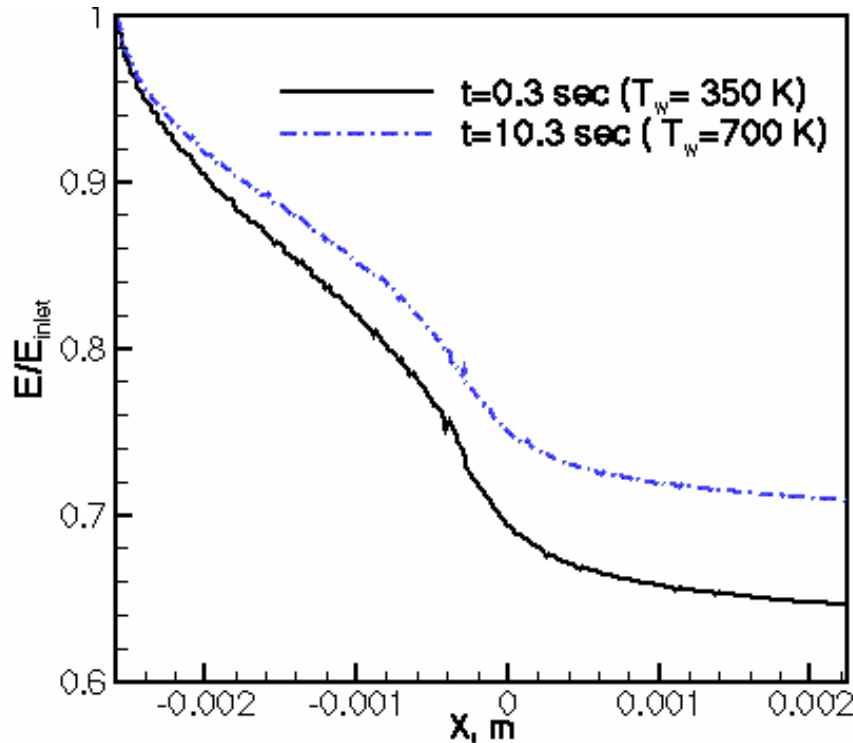
# Micronozzle performance

$h=600\text{ }\mu\text{m}$ ,  $p_o=0.1\text{ atm}$ , insulated vs cooling



- Final thrust value,  $F$ , are 15% and 6% lower than the initial ones for Case 1 and 2, respectively.
- The mass flow degradation is as much as 55% in Case 1.
- Coeff. of mass discharge,  $C_d$ , decreases more rapidly than  $F$ .

# Where does the energy go?



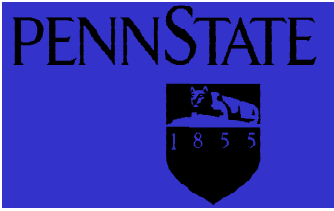
**Ratio of gas energy to value at inlet  
along the nozzle axis.**

- **2-D,  $p_0=0.5$  atm, cooling, (AIAA 03-0673).**

- **Cooling allows heat transfer losses.**

- **As material heats up, less gas energy is transferred to the wall.**

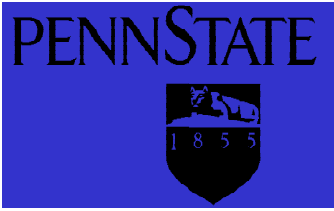
- **As material heats up, reduction in thrust will slow down.**



# Conclusions

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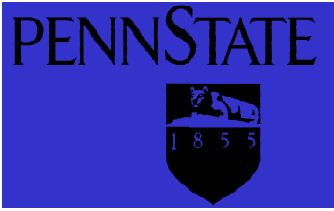
- **Material thermal response is similar to 2D, but gas flow structure is significantly different due to the side-wall boundary layer.**
- **For thermal cooling, the steady-state material temperature is 450 K (same as in 2D).**
- **Higher Re flow results in larger surface heat fluxes and, thus, shorter operational times. However, heat fluxes do not vary proportionally with Re.**
- **Cooling applied to the outer surface can sustain the material temperature below melting. Cooling results in improved thrust and mass discharge performance.**
- **The large temporal variation of the thrust, and especially mass discharge coefficient means that the coupling between the gas and material must be taken into account in micropropulsion design.**



## Related Publications

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1. Alexeenko, A., Fedosov, D., Levin, D., Gimelshein, S., and Collins, R., "Transient Heat Transfer and Gas Flow in a MEMS-based Thruster," submitted to the *IEEE J. of MEMS*, April 17, 2003.
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